

Aug. 6, 1940.

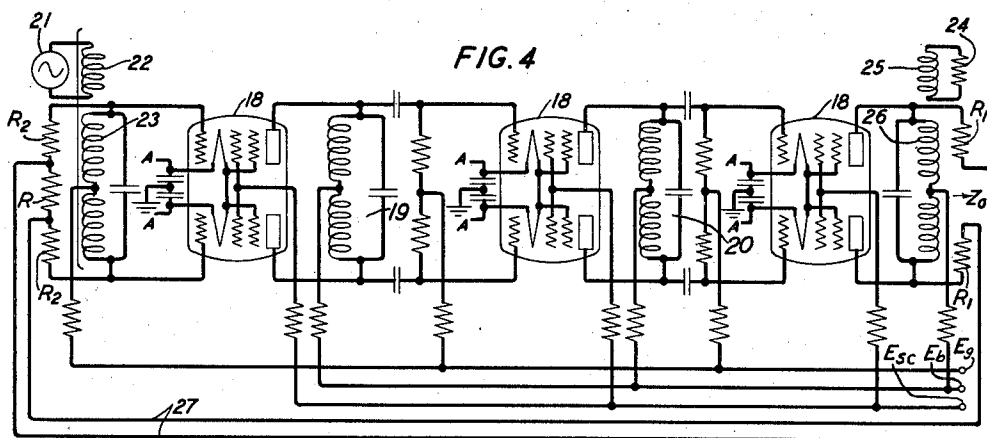
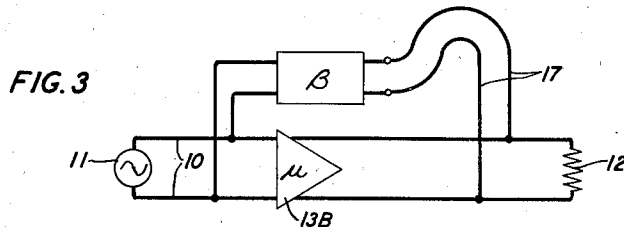
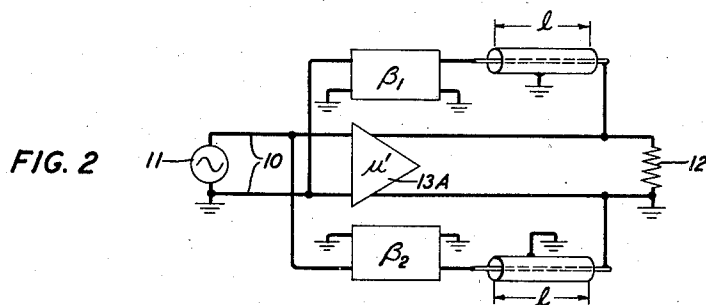
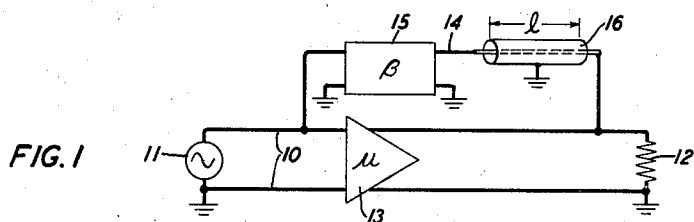
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2,210,503

WAVE TRANSLATION SYSTEM

Filed Oct. 25, 1938

5 Sheets-Sheet 1



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FIG. 5

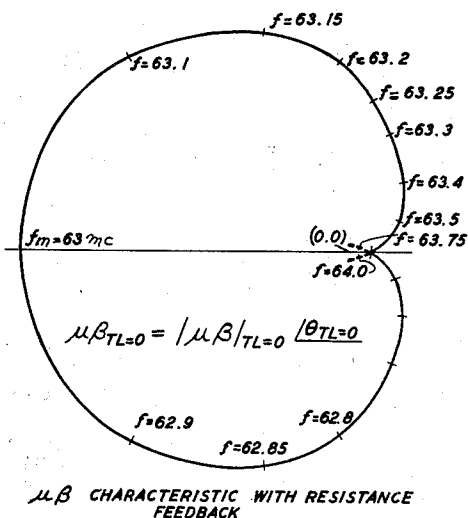


FIG. 6

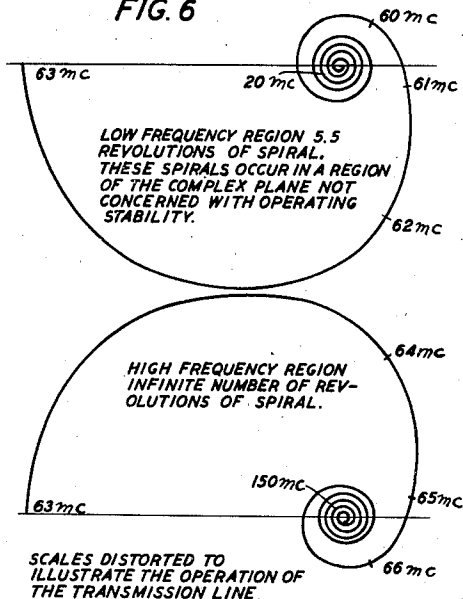
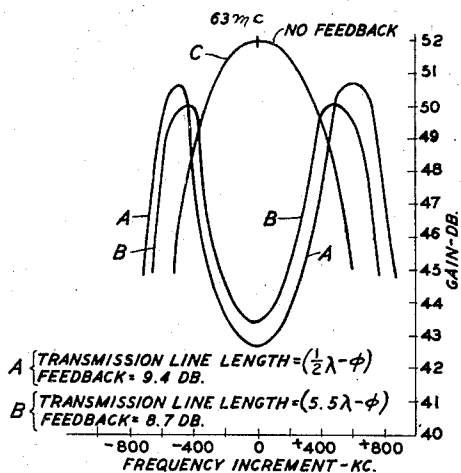


FIG. 7



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WAVE TRANSLATION SYSTEM

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FIG. 8

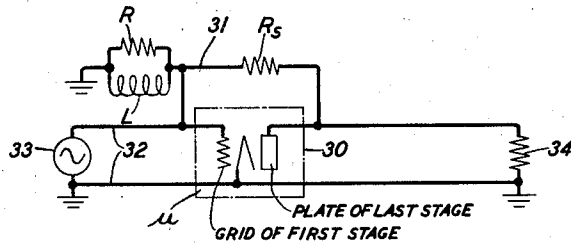


FIG. 9

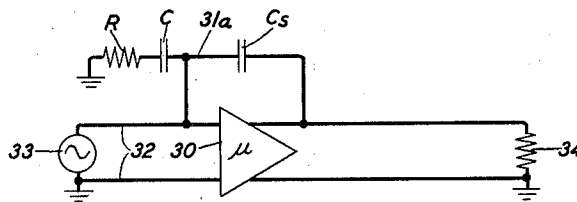


FIG. 10

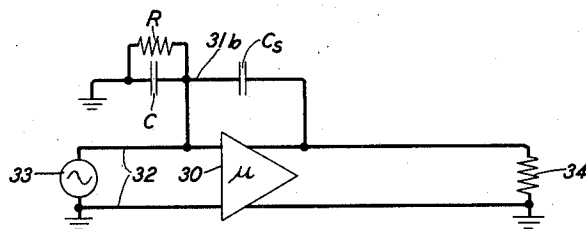
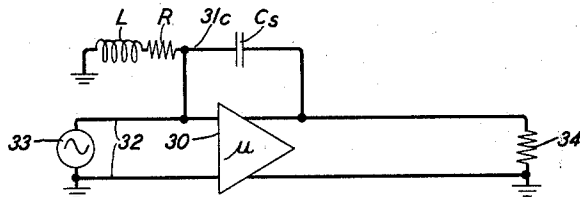


FIG. 11



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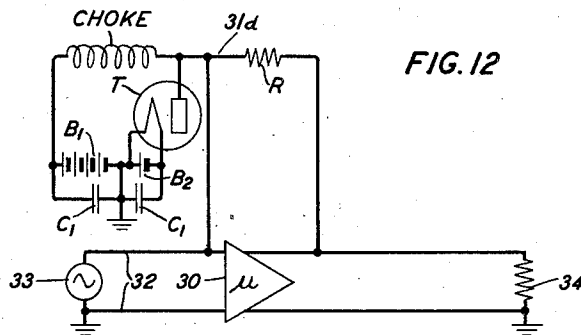


FIG. 12

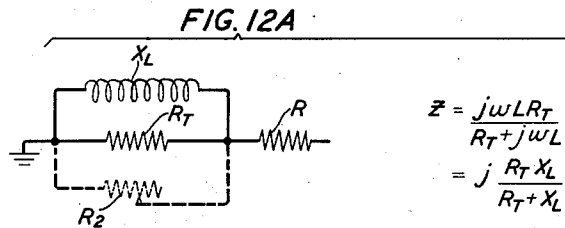


FIG. 12A

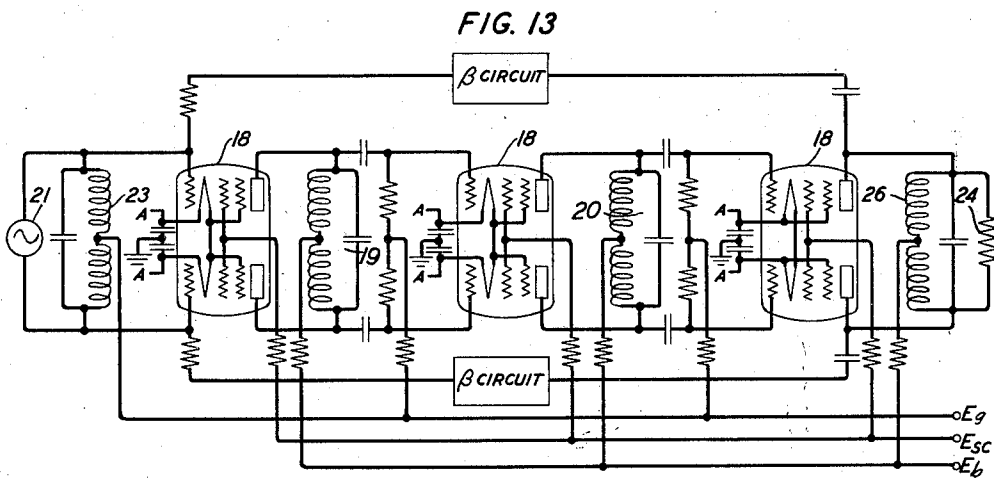


FIG. 13

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FIG. 14

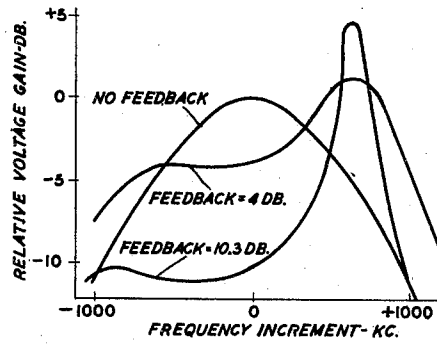


FIG. 15

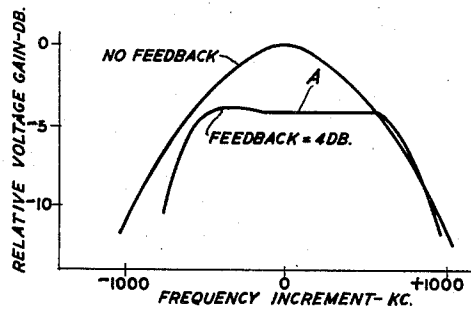
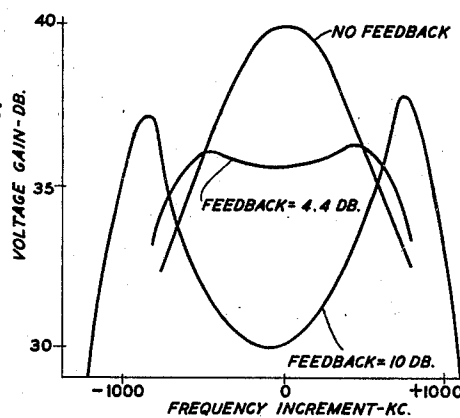


FIG. 16



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UNITED STATES PATENT OFFICE

2,210,503

WAVE TRANSLATION SYSTEM

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Application October 25, 1938, Serial No. 236,857

9 Claims. (Cl. 179-171)

The present invention relates to amplifiers.

Amplifiers including a negative feedback connection for feeding back a portion of the amplifier output to the input of one of the stages of the amplifier, in such magnitude and phase as to cause a substantial reduction in the over-all gain of the amplifier with resultant marked improvement in stability and reduction in noise and distortion, are known, for example, in H. S. Black Patent 2,102,671, issued December 21, 1937. In applying the Black negative feedback principle to amplifiers of high frequencies, particularly those of the order of millions of cycles, phase shift problems are encountered that appear not to exist at relatively lower frequencies.

The unwanted phase shift may be contributed by the tubes or electron discharge devices, tube leads or the physical length of the feedback loop. Of the several possible sources of deleterious phase shift, two appear to be of major importance: First, that due to the effect of electron transit time in the tubes; this effect is inherent in electron discharge devices and, therefore, it cannot be eliminated entirely but must be compensated for; second, that due to the physical length of the feedback loop. For example, in high power short wave amplifiers, the size of tubes and the spacing of component parts of an amplifier to meet high voltage insulation requirements may result in a physical length of the $\mu\beta$ -path of a negative feedback amplifier which is a considerable fraction of a wave-length. A similar condition may exist at audio or carrier frequencies in repeater systems where feedback is desired over two or more amplifiers separated by several miles of interconnecting lines. In most cases, the deleterious phase shift is principally a lagging phase shift in the $\mu\beta$ -path of the amplifier and must be corrected if maximum performance is demanded from the amplifier or transmission system.

The unwanted phase shift may be corrected, it has been determined, by using lumped constants in the feedback circuit to introduce a leading phase shift providing the desired resultant phase shift around the feedback loop; or, it may be corrected by using a transmission line in the feedback circuit, or between stages of the amplifier, the length of the line being such that the necessary phase shift is introduced to provide the desired resultant phase shift around the feedback loop. Aside from its use in compensating for unwanted phase shift in an ultra-high frequency amplifier, the transmission line may be used in any feedback amplifier to intro-

duce a desired or preassigned delay in the feedback circuit.

Objects of the invention are to apply the negative feedback principle to amplifiers of high frequencies with results comparable to those obtained at relatively lower frequencies, and to compensate effectively for unwanted phase shifts arising from the use of such high frequencies.

A feature of the invention comprises compensating for unwanted phase shift in the μ - or forwardly transmitting portion or path of an amplifier by use in the β - or backwardly transmitting portion or path of the amplifier of a circuit of either lumped or distributed constants introducing a phase shift that compensates for the unwanted phase shift.

A more complete understanding of the invention will be obtained from the detailed description which follows hereinafter, taken in conjunction with the appended drawings, wherein:

Fig. 1 is a schematic of a transmission system including a feedback amplifier having a transmission line in its feedback path;

Fig. 2 is a schematic of a system similar to that of Fig. 1 except that the amplifier is of the push-pull type;

Fig. 3 is a schematic of a system similar to that of Fig. 1 except that an open-wire transmission line is used rather than the concentric conductor transmission line of Fig. 1;

Fig. 4 is a circuit drawing of an ultra-high frequency amplifier including a transmission line in its feedback path;

Fig. 5 shows a $\mu\beta$ -characteristic for the amplifier of Fig. 4 with a resistance feedback only;

Fig. 6 shows an approximate $\mu\beta$ -characteristic for the amplifier of Fig. 4 with a transmission line providing a number of cycles delay in the feedback circuit;

Fig. 7 shows gain-frequency characteristics for the amplifier of Fig. 4 for conditions of no feedback and for feedback provided by transmission lines of different lengths;

Fig. 8 is a schematic of an ultra-high frequency amplifier including a β -circuit having lumped constants for correcting for unwanted phase shift due to the effect of electron transit time;

Figs. 9, 10, 11 and 12 are schematics of amplifiers similar to that of Fig. 8 but including β -circuits having different configurations;

Fig. 12A shows the equivalent circuit for the β -circuit of Fig. 12;

Fig. 13 is a circuit drawing of an amplifier similar to that of Fig. 4 but having a lumped con-

stant β -circuit in place of a transmission line;

Fig. 14 illustrates the effect of the phase angle of tube transconductance on the gain-frequency characteristics of the amplifier of Fig. 13 in the case of a resistance feedback; and

Figs. 15 and 16 illustrate the symmetrical gain-frequency characteristic that can be obtained with the amplifier of Fig. 13 when the β -circuit is designed to compensate for the phase angle of tube transconductance.

The $\mu\beta$ -characteristic of a feedback amplifier operating at low frequencies may be expressed as $\mu\beta = |\mu\beta| |\theta + \varphi|$ where: $|\mu\beta|$ is the absolute value of $\mu\beta$; θ is the phase advance or lag due to circuit elements and which is variable with frequency; φ is a constant phase, due, for example, to the vacuum tubes, invariable with frequency. In the simple three-stage, shunt-shunt feedback amplifier, $\varphi = 3 \times 180$ degrees or 180 degrees. At some particular frequency, usually at mid-band, θ is made equal to zero and the feedback voltage is exactly 180 degrees out of phase with the applied voltage. As the frequency is varied the phase θ will also vary and will be added to or subtracted from the constant phase φ . The desired characteristic in the $\mu\beta$ -loop may be obtained by using the principles of H. W. Bode Patent 2,123,178, issued July 12, 1938.

Turning to amplifiers operating at higher frequencies a different problem exists. The phase φ which was termed constant at low frequencies now becomes dependent on frequency and in many instances becomes an appreciable fraction of a cycle. This deleterious phase shift may be contributed by the tubes, leads or physical length of the feedback loop. For the most part these circuits are of the distributed constant type which contribute phase shift with negligible attenuation.

At ultra-high frequencies a major source of deleterious phase shift is that due to the effect of electron transit time. This effect is inherent in electron discharge devices so that it cannot be eliminated entirely, but must be compensated for. If such a phenomenon exists in a particular amplifier, that is, if the time of transit of the electrons from the cathode to the anode becomes an appreciable portion of a cycle of the operating frequency, an effective delay is introduced into the amplifier tube transconductance. Thus the developed plate voltage, with a resistive plate load, will be out of phase with the grid voltage by 180 degrees minus φ_T degrees instead of the usual 180 degrees, where the lagging angle in the tube transconductance is φ_T degrees. In the published work of F. B. Llewellyn (Proceedings of the Institute of Radio Engineers, vol. 22, August 1934) it is shown that the transit angle of a triode may be expressed as follows:

$$\text{transit angle} = \frac{kx}{\lambda\sqrt{v}} = \frac{k'fx}{\sqrt{v}}$$

where:

k and k' are constants
 x —cathode to anode spacing—cm.
 λ —operating wave-length—cm.
 v —anode voltage—volts
 f —frequency—c. p. s.

If these factors are known Llewellyn shows that the transit time may be calculated and in turn the effective phase angle φ_T of the transconductance determined. Referring to the above equation, it may be noted that the transit angle varies with voltage and with frequency. The

variations due to voltage changes may be neglected except in special instances not dealt with here; the variations due to frequency changes as well as the absolute value of frequency are, however, of first order importance. The effect due to frequency will be examined further. First, in order to obtain some idea of the magnitudes involved it may be stated that a Western Electric twin pentode tube, Type 240-HH, operating at 63 megacycles, ($E_b=400$ v.) had an effective measured angle φ_T in its transconductance of about -15.3 degrees. Three stages would have about -46 degrees. This means that at mid-band frequency, in an amplifier using these three stages, the input grid voltage and the output plate voltage are out of phase by 180 degrees minus 46 degrees or about 134 degrees. If this output voltage is fed back directly to the grid of the first stage (with no change in phase) the desired condition for feedback at mid-band frequency (input and output voltages 180 degrees out of phase) is not fulfilled. Both gain and phase margins against instability are reduced. The resultant effect is a reduction in the amount of feedback before singing occurs, bad dissymmetry in the gain-frequency characteristic, and a decrease in the width of the useful frequency band.

The equation for this amplifier may be expressed as:

$$\mu\beta = |\mu\beta| |\theta + \varphi + \varphi_T| = |\mu\beta| e^{i(\theta + \varphi)} \times e^{i\varphi_T}$$

where $|\mu\beta|$, φ and μ are the same quantities as in the low frequency case, and

$$\varphi_T$$

is the phase angle in the μ - or forward path due to the effective phase angles of the tube transconductances.

$$\varphi_T$$

may also be due to the fact that the apparatus is an appreciable fraction of a wave-length in size. It may be noted that this $\mu\beta$ -equation is identical with the low frequency condition except for the multiplication by a phase shift due to transit time.

Before considering methods of compensation for the angle

$$\varphi_T$$

it is desirable to know its value not only at mid-band frequency but also at the critical frequencies of gain and phase cross-over. The ideal compensating circuit would be one which corrected

$$\varphi_T$$

exactly for all frequencies. This is theoretically possible but in most practical cases such perfect correction is not needed and simple circuits providing approximate compensation will suffice. For convenience, we may divide the methods of correction into two classes: (1) Those dealing with amplifiers where the variation of

$$\varphi_T$$

across the frequency band between the phase cross-over frequencies is small and the margins of gain and phase are sufficient. This condition is nearly always present at high radio frequencies where the ratio of the critical frequency band (arbitrarily defined as the frequency difference between phase cross-over frequencies) to the absolute mid-band frequency is small—in the

order of a few per cent; (2) those dealing with the condition where the variations in

$$\varphi_T'$$

5 across the critical band cannot be neglected. This condition is most often met in the low frequency range. There the ratio of the critical frequency band to the absolute mid-band frequency is large.

10 For amplifiers in class (1) the design would be made in two steps. The phase angle

$$\varphi_T'$$

would be compensated for by methods discussed hereinafter. Then the amplifier circuits would be designed as suggested in the Bode patent. For amplifiers in class (2) the excess phase shift

$$\varphi_T'$$

20 would be compensated for by altering the design of the amplifier using Bode's methods. Methods of compensation for

$$\phi_T'$$

25 which might be used in the first class will now be considered. For simplicity, the correction will be made first for a single frequency. This may be done by increasing the delay in the $\mu\beta$ -loop so that the total phase lag will be a complete cycle or 360 degrees. This can be accomplished by using a distributed constant network, such as a transmission line. The line introduces phase shift with negligible attenuation.

This is illustrated by Fig. 1. The transmission line 10 has a source 11 of signal waves connected across its input terminals, and a suitable load or terminating impedance 12 connected across its output terminals, a feedback amplifier 13 being connected in the transmission line. The amplifier, for example, for amplifying very high frequencies, of the order of megacycles, comprises a μ - or forward path that may be, for example, a three-stage amplifier, and a feedback connection 14. Ordinarily, the feedback connection would include merely the transmission element 15, for instance, a resistance or other impedance, labeled β . To compensate for the undesired phase shift in the μ -path, resulting from the effect of electron transit time in the tubes in the μ -path, the transmission line or concentric cable 16 of length l is introduced in the feedback connection and may be considered as part of the β - or backwardly transmitting path of the amplifier. The transmission line would be terminated, preferably, in a resistance equal to its surge impedance. The length l of line inserted should be equal to

$$\lambda \left(n - \frac{\varphi_T'}{360} \right)$$

60 where λ is the wave-length at which the correction is desired,

$$\varphi_T'$$

is the undesired phase shift in degrees and n is a positive integral number, 1, 2, 3, etc. The $\mu\beta$ -equation may now be written as

$$\mu\beta_{\text{uncorrected phase angle}} = |\mu\beta| e^{i(\theta+\varphi)} \cdot e^{i\varphi_T'}$$

and

$$\mu\beta_{\text{corrected phase angle}} = |\mu\beta| e^{i(\theta+\varphi)} \cdot e^{i\varphi_T'} \cdot e^{i\frac{\phi_T'}{360} \left(n - \frac{\varphi_T'}{360} \right)}$$

$$= |\mu\beta| e^{i(\theta+\varphi)} \cdot e^{i\frac{\phi_T'}{360} n}$$

$$\doteq |\mu\beta| e^{i(\theta+\varphi)}$$

If desired, the termination of the compensating line may be different from a resistance equal to its surge impedance provided that the new termination is taken into account, using well-known transmission line formulae, in the $\mu\beta$ -equation in setting up the requirements for feedback. Under this condition, the required length of transmission line and its value of surge impedance will depend on the characteristics of the terminating impedance. In this instance the transmission line in conjunction with its terminating impedance might serve the dual functions of the phase shift and attenuation required in the β -section of the amplifier. Other physical characteristics of the line, such as the material of which it is constructed, may be altered to produce desired results.

It is realized that if the unwanted phase shift

$$\varphi_T'$$

should be positive in a particular transmission system, the length of line required for compensation will be

$$l = \lambda \left(n' + \frac{\varphi_T'}{360} \right), n' = 0, 1, 2, 3, \text{ etc.}$$

In the example described above the compensating line was shown connected in the β -path. It is possible to insert the line at any point in the $\mu\beta$ -loop. For example, it may be in the μ - or forwardly transmitting portion or path, and might be inserted between stages of a multistage amplifier or between amplifiers, when the feedback is around a plurality of amplifiers at intervals along a transmission line.

If the amplifier has an even number of stages, or if it has an odd number of stages but means are included to produce an additional phase shift of 180 degrees, the length of the line required may be reduced. In such case,

$$l = \lambda \left(.5m - \frac{\varphi_T'}{360} \right)$$

where m is an odd positive integer, 1, 3, 5, etc., λ =wave-length at which correction is desired, and

$$\varphi_T'$$

is the total undesired phase shift in degrees. Fig. 2 is representative of a push-pull amplifier, for example, of a single stage with the feedback connection from the output of one tube to the input of the other tube. In each feedback connection, the length of the transmission line need be only

$$\lambda \left(.5m - \frac{\varphi_T'}{360} \right)$$

instead of

$$\lambda \left(n - \frac{\varphi_T'}{360} \right)$$

which would be the case if the feedback connections were from the output of one tube to the input of the same tube. Of course, if no compensation for undesired phase shift were necessary, $l = .5m\lambda$ rather than $n\lambda$.

An open-wire compensating line 17 may be used as shown in Fig. 3.

Fig. 4 shows the application of the invention to a multistage negative feedback amplifier, designed to operate at 63 megacycles and embodying an open-wire transmission line.

The amplifier comprises a three-stage push-pull amplifier, each stage comprising a twin pentode 18 of the type disclosed in A. L. Samuel Patent 2,062,334, issued December 1, 1936. The in-

terstage networks 19, 20 are of simple, anti-resonant type. Control grid, plate and screen grid potentials are supplied from sources E_g , E_b and S_{sc} , respectively. Heating current for the cathodes, which, of course, could be of the indirectly heated type, is supplied through points A, A. The source 21 of high frequency signal to be amplified may be inductively coupled through the windings 22, 23 to the input circuit of the first stage of the amplifier, and the load 24 to which the amplified signal is being transmitted may be inductively coupled through the windings 25, 26 to the output circuit of the last stage of the amplifier. A feedback connection comprising an open-wire transmission line 27 connects the output of the amplifier with the input of the amplifier, the line 27 being terminated at the input of the amplifier in a resistance R equal to the surge impedance Z_0 of the line, the equal resistances R_2 each being much larger than R . The input impedance of the line serves as the shunt element of the β -circuit potentiometer and the equal resistances R_1 are connected between each side of the line and the output plate circuit to serve as series elements of the β -circuit potentiometer. The resistances R_2 also serve as series elements of this potentiometer.

The operation of the transmission line in the β -circuit of this ultra-high frequency amplifier may be described as follows. The feedback signal, originating in the plates of the last stage, is transmitted through the line to the input circuit of the first stage. The line introduces phase shift with negligible attenuation. Thus, the effect of the line is to rotate the phase of the fed-back voltage by an amount depending on the length of line. If the length of line is one-half wave-length, the phase shift will be 180 degrees at mid-band frequency. For frequencies well separated from mid-band, however, different phase shifts will occur. If the gain remained large, these might not be desirable. In practice, however, such latter phase shifts occur in a region of the frequency spectrum which has little effect on the stability. Thus, with certain limitations, any integral number of half wave-lengths of line may be used.

Returning the feedback through a transmission line offers a number of advantages. The output and input circuits of the amplifier may be physically separated. This eliminates the strict requirement heretofore imposed in feedback amplifier design that the path of the voltage fed back be not only as short as possible but be negligibly short. At ultra-high frequencies, as in high power short wave systems, of course, this is of major importance. Furthermore, it is possible at one frequency to introduce in the β -circuit of an amplifier any phase angle whatsoever by the simple expedient of adjusting the length of line to the required number of electrical degrees. The use of a transmission line, also, would permit feedback around antennas, thus including feed lines and antennas within the $\mu\beta$ -loop so that they can be operated on by the feedback to improve or change their characteristics.

The performance of an amplifier with a transmission line in its β -circuit is best analyzed by means of its $\mu\beta$ -characteristic. Consider the three-stage amplifier shown in Fig. 4. With a pure resistance feedback and no transmission line therein the $\mu\beta$ -characteristic may be expressed by the equation;

$$\mu\beta_{TL=0} = |\mu\beta|_{TL=0} |\theta_{TL=0}|$$

Plotted for a particular set-up of the amplifier, the curve of Fig. 5 is obtained. If a transmission line of length l is inserted in the β -circuit, the general equation for $\mu\beta_{TL=l}$ is

$$\mu\beta_{TL=l} = |\mu\beta|_{TL=0} \left| \theta_{TL=0} + \frac{2\pi l}{\lambda} \right|$$

where λ is the wave-length at the particular frequency for which $\mu\beta_{TL=l}$ is being computed. The attenuation of the line is assumed negligible. The $\mu\beta_{TL=l}$ -characteristic will be a system of spirals: the low frequency region extending from zero to the neighborhood of the useful band will have a finite number of revolutions equal to the number of mid-band wave-lengths in the transmission line; the high frequency region, extending from the useful band to finite frequency, will have an infinite number of revolutions. Such a characteristic for an amplifier having a transmission line of 5.5 wave-lengths is shown in Fig. 6. For this line the phase shift in the β -circuit at mid-band frequency is 1980 degrees. In most practical cases, the stability of the amplifier with the line will not be greatly affected from the condition existing without the line. This results from the fact that the inner revolutions of the $\mu\beta$ -characteristic, as plotted in the complex plane, will occur in a region which is not significant in the consideration of operating stability: namely, well within a radius of unity from (0,0).

Difficulties may be expected, however, when the differential phase shift introduced by the line in the frequency range of interest becomes large. This phase shift may be readily calculated. Let the length of line $=l$, and the time delay $=\tau$.

$$\tau = \frac{l}{c}$$

where c =velocity of propagation.

The differential phase shift ψ_{1-m} from the mid-band frequency f_m to some other frequency f_1 will be

$$\psi_{1-m} = \psi_1 - \psi_m = \frac{2\pi l}{\lambda_1} - \frac{2\pi l}{\lambda_m}$$

where

$$\lambda_1 = \frac{c}{f_1}$$

and

$$\lambda_m = \frac{c}{f_m}$$

$$\psi_{1-m} = \frac{2\pi l}{c} (f_1 - f_m)$$

$$\psi_{1-m} = \frac{2\pi l}{c} \gamma$$

where

$$\gamma = (f_1 - f_m)$$

$$\therefore \psi_{1-m} = \frac{2\pi l}{\lambda_\gamma}$$

where λ_γ is the wave-length corresponding to the differential frequency γ .

If the tolerable phase shift at some critical frequency is known, the maximum permissible length of line can be determined. For example, if the limiting phase shift is

$$\frac{\pi}{10} \text{ radians}$$

at a frequency removed from mid-band 3×10^6 cycles/sec. then

$$\psi_{1-m} = \frac{\pi}{10} = 2\pi l \cdot \frac{3 \times 10^6}{3 \times 10^8}$$

$l=5$ meters.

If it is assumed that in a particular amplifier, the mid-band frequency is 150 megacycles, i. e., $\lambda_m = 2$ meters; the maximum length of transmission line would be about 3 wave-lengths.

The actual performance of an amplifier with transmission line feedback was investigated in an amplifier in accordance with Fig. 4. First, a 0.5λ line was used and its length changed to compensate for the transit angle; then, the transit angle of the amplifier was changed and the length of the line was varied to compensate for this change (this showed the feasibility of using a feedback transmission line to measure transit angles); then, a long line of 5.5λ was employed. In each case, the amount of feedback was about 10 decibels and the criterion for proper adjustment of the line was that the gain-frequency curve of the amplifier be symmetric about the mid-band frequency. The use of a line an odd number of half wave-lengths in length requires one transposition to obtain the correct phase relations. This was the condition in each test.

In the first case, it was found necessary to reduce the length of the line from

$$\frac{\lambda}{2}$$

or 238 centimeters to 184 centimeters in order to obtain the symmetric gain-frequency curve A of Fig. 7. This corresponds to a change of 40 electrical degrees and compensates for the phase shift due to the effect of transit time in the tubes. In making this measurement, all capacitive effects across the line were neglected, and the amplifier was operated with the plate and screen grid voltages at half normal value. There was no evidence of instability.

In the second case, the plate voltage was increased on two stages of the amplifier by a factor of two. A symmetric gain-frequency characteristic was obtained by increasing the length of the transmission line from 184 centimeters to 197 centimeters, corresponding to a change of 9 electrical degrees, or to a decrease in the transit angle in each of the two stages of 4.5 degrees. According to theory, there is to be expected as a first approximation a decrease per stage of

$$15 - \frac{15}{\sqrt{2}}$$

or 5 degrees. Measurement, therefore, was in good agreement with theory.

In the third case, 5.5λ of line replaced the 0.5λ section. To obtain the proper compensation for the phase angle of the transconductance, the line was reduced in length by about 65 centimeters. The gain-frequency characteristic of the amplifier with this long line ($5.5\lambda_{63mc.} = 26.18$ meters) in its feedback circuit is shown by curve B of Fig. 7. Curve C is a gain-frequency characteristic for the amplifier of Fig. 4 with no feedback present.

From what has been detailed hereinabove, it is apparent that it is feasible to insert a transmission line of one or more half wave-lengths in the β -circuit of a feedback amplifier, and that by adjustment of its length compensation may be provided for the phase angle of the transconductances of the tubes. In high power short wave amplifiers, a

$$\frac{\lambda}{2}$$

line may provide a practical feedback path without materially reducing the amount of feedback

possible. Furthermore, the line may be used to measure transit angles and changes in transit angles, and to introduce any desired number of cycles delay in a feedback circuit.

It is known in the art that the over-all envelope delay, as distinguished from the delay around the loop, of a feedback amplifier using a large amount of feedback, is the negative of the envelope delay in the β -circuit. Thus, an envelope delay in the β -circuit would actually result in an advance of the envelope. It seems possible, therefore, that a feedback amplifier with a transmission line in its β -circuit might be used to provide a desired envelope advance, e. g., an envelope feedback loop with a radio frequency feedback loop inside it, the radio frequency loop containing a radio frequency transmission line in its β -circuit.

In many instances it will be more convenient to use circuits containing lumped constants for effecting compensation or correction for the deleterious phase shift in a transmission system by introducing a leading phase shift in the $\mu\beta$ -path. The circuit may perform the function, also, of providing the desired attenuation in the β -path. That is, the circuit may serve both as the β -path potentiometer and the phase correcting means.

Fig. 8 is a schematic of a three-stage high frequency amplifier 30 having a feedback or β -path 31. The amplifier is shown in a transmission line or path 32, a source 33 of high frequency signal being connected to the terminals of one end of the line, and a load 34 into which the amplifier works being connected to the terminals of the other end of the transmission line. The β -path 31 comprises a series resistance R_s and a shunt impedance Z comprising a resistance R and an inductance L in parallel. R_s and the impedance looking toward the input grid from the shunt circuit $R||Z$ should be high with respect to Z and the impedance of the β -path should be large with respect to the plate impedance in the output of the amplifier. This is the condition usually met in practice. If such is not the case, the simplified equation used below cannot be employed. The familiar general circuit equations may then be used which take all elements into consideration. From these equations the magnitude and phase of the fed-back voltage e_β relative to the applied voltage e_a may be expressed in terms of the circuit elements in the β -network. From this, the correct values may be assigned to the elements in the β -network to provide the desired amplitude and phase of the fed-back voltage e_β . For the condition usually met in practice, the voltage, e_g , impressed on the input grid is equal to the signal voltage e_a plus the fed-back voltage e_β . A current

$$i = \frac{e_p}{R_s + Z} \quad 60$$

flows in the feedback circuit, and with

$$R_s > Z, i = \frac{e_p}{R_s} \quad 65$$

where e_p is the developed plate voltage. Now $e_\beta = Zi$, where Z has the angle

$$\phi'_T$$

the angle to be compensated for, where

$$\phi'_T = \tan^{-1} \frac{R}{\omega L}$$

The ratio of the impedances of the shunt section Z to the series section R_s is selected to give the

desired attenuation in the β -path; the phase angle of the shunt section is chosen so that it is equal to

$$\varphi_T$$

the total unwanted phase shift resulting from the effect of transit time. If, in the particular case,

$$\varphi_T = 45 \text{ degrees}$$

then

$$\tan^{-1} \frac{R}{\omega L} = 45 \text{ degrees}$$

and $R=L$. This circuit may be arranged to compensate exactly for

$$\varphi_T$$

at mid-band frequency, introducing a leading phase shift to compensate for the lagging phase shift due to the effect of transit time.

Fig. 9 shows another circuit 31a for the β -path. The series section comprises a capacitance C_s and the shunt section Z comprises a resistance R and a capacitance C in series. If

$$\varphi_T$$

is the phase angle of the tube transconductances to be corrected for, the phase angle of Z should be chosen such that

$$\tan^{-1} \frac{1}{\omega CR} = 90 \text{ degrees} - \varphi_T$$

In Fig. 10, the circuit 31b for the β -path is shown as comprising a capacitance C_s for its series section and its shunt section a capacitance C and a resistance R in parallel. Here

$$Z = \frac{1}{\sqrt{\frac{1}{R^2} + \frac{1}{X^2}}}$$

and its phase angle should be

$$\tan^{-1} \omega CR = 90^\circ - \varphi_T$$

With the arrangements of Figs. 8, 9 and 10, compensation may be made for angles up to about 90 degrees. It might be pointed out that the magnitudes of Z and the phase correcting angles may not be symmetrically displaced about the mid-band frequency as the frequency is varied, but in most practical cases this lack of symmetry will not be a source of trouble.

In Fig. 11, there is shown a lumped constants circuit 31c for providing corrective or compensating phase shifts of from 90 degrees to 180 degrees. In this case, the β -series section is a capacitance C_s and the shunt section comprises an inductance L and a resistance R in series,

$$Z = \sqrt{R^2 + X^2}$$

the phase angle of Z being

$$\tan^{-1} \frac{\omega L}{R} = \varphi_T - 90 \text{ degrees}$$

In Fig. 12, the use of a vacuum tube for the compensation of unwanted transit time phase shift is shown. The tube is chosen so as to have an angle in its effective interval impedance

which may be used for correction purposes. Fig. 12A shows the equivalent circuit for the β -circuit, 31d. R_2 is an external resistance or other element that may be employed to control the desired angle and attenuation in the β -circuit.

For compensating for the unwanted angle,

$$\tan^{-1} \frac{R_T}{X_L} = \varphi_T$$

the operation of the circuit being similar to that of Fig. 8. C_1, C_2 are by-pass condensers, B_1 and

B_2 are plate and filament heating battery, respectively.

The circuit of Fig. 12 could be employed, also, to compensate for variations in

$$\varphi_T$$

due to voltage changes in the μ -path of the amplifier. The characteristic of the tube T would be such that as the voltage fed back to its plate varies in amplitude, the phase of the effective interval impedance of the tube T varies to compensate for the variation in

$$\varphi_T$$

Although the tube T is shown as a diode, other types of tubes may be used.

Fig. 13 is a circuit drawing of a three-stage amplifier designed to amplify a signal frequency of 63 megacycles and to provide a feedback of 10 decibels. Its similarity to that of Fig. 4 is evident, like parts bearing corresponding identifying characters, but the transmission line feedback is not included. It has been determined that if no compensation is provided for the phase angle of the tube transconductances, there is bad dissymmetry in the gain-frequency characteristic, a reduction in the permissible amount of feedback before singing occurs, and a decrease in the width of the useful frequency band. This is brought out clearly when the β -circuit of the amplifier of Fig. 13 consists of a pure resistance in its series section and a pure resistance to ground in its shunt section. Fig. 14 shows the gain-frequency characteristic for such an amplifier for a condition of no feedback, or negative feedback at mid-band of about 4 decibels, and of negative feedback at mid-band of about 10 decibels; the feedback extends over a range from about 62 to 64 megacycles. Similar results would be obtained if the resistances of the β -circuit were replaced by pure capacitances. When the β -circuit comprises, however, one of the transit time phase angle compensating circuits of Figs. 8 to 12A, a symmetrical gain-frequency characteristic is obtainable. Using the β -circuit of Fig. 9, the amplifier of Fig. 13 had the gain-frequency characteristic of curve A, Fig. 15, taken for a negative feedback of 4 decibels with the phase angle of the tube transconductances exactly compensated at the mid-band frequency of 63 megacycles. In the particular amplifier, the phase lag due to the effect of transit time was about 46 degrees. The combination of resistance and capacity in the β -shunt section was designed to have a phase angle of 44 degrees, i. e., 90 degrees minus 46 degrees, the voltage developed across the shunt section lagging the current through the shunt section by 44 degrees. When the parallel resistance and condenser of Fig. 9 were replaced by a resistance and the parallel arrangement introduced in the series section in place of the condenser, the symmetrical gain-frequency characteristics of Fig. 16 were obtained for conditions of mid-band feedback of 4.4 decibels and of 10 decibels.

In connection with Fig. 8, it was stated that the β -circuit arrangement of that figure could be proportioned so as to compensate exactly for

$$\varphi_T$$

at mid-band frequency. This may not be the condition, however, at the critical frequencies of gain or phase cross-over. It is possible, however, to select circuits so that the phase margin may be improved. This may be done by using

a circuit in which the correcting angle varies with frequency in the same direction as the unwanted angle. This is illustrated in the table below which shows the variation in

ϕ_T (arbitrarily assuming $\phi_T \propto f^2$)

across the critical band of a 63-megacycle amplifier such as that of Fig. 13 using the compensating circuits of Figs. 9 and 10.

f -mc	Total unwanted phase shift ϕ_T	Value of compensating angle—Fig. 10 circuit	Difference between ϕ_T and compensating angle of Fig. 10	Value of compensating angle—Fig. 4 circuit	Difference between ϕ_T and compensating angle of Fig. 9
	Degrees	Degrees	Degrees	Degrees	Degrees
63=mid-band	-45	+45	0	+45	0
61-----	-43.5	+46	+2.5	+44	+1.5
65-----	-46.5	+44	-2.5	+46	-1.5

From this table, which shows the effect of two different compensating circuits whose phase angles vary in opposite directions with frequency, it is evident that improvement is obtained in a particular case by selection of the most appropriate circuit. If more complicated feedback circuits are employed, exact compensation over the entire critical frequency band may be obtained.

Although this invention has been disclosed with reference to various specific embodiments, it is to be understood as not limited thereto but by the scope of the appended claims only.

What is claimed is:

1. An amplifier comprising a μ - or forward path having a phase shift due to the effect of electron transit time, and a β - or backward path including means to compensate for said phase shift.

2. An amplifier as claimed in claim 1 in which the phase shift is a lagging phase shift, and said means comprises a lumped constants circuit introducing a leading phase shift correcting for said lagging phase shift.

3. An amplifier as claimed in claim 1 in which said means comprises a transmission line of length

$$l = \lambda \left(n - \frac{\phi}{360} \right)$$

where l =length in meters, λ is the wave-length in meters of the mid-band frequency of the frequencies amplified, n is a positive integer, 1, 2, 3, etc., and ϕ is the total phase angle for which compensation is to be provided.

4. In a high frequency amplifying system, an electron discharge device having an input electrode and an output electrode, a source of high

frequency energy connected to said input electrode, the frequency being so high that there is a phase shift additional to the normal phase shift between the input and the output voltage of said device, and a negative feedback circuit compensating for said additional phase shift.

5. In a high frequency amplifying system, an electron discharge device in which the energy to be amplified is of such high frequency that the phase shift between the input and output voltage of said device is 180 degrees minus ϕ degrees, where ϕ degrees is a phase shift due to the effect of electron transit time, and a feedback circuit including means compensating for said phase shift.

6. An amplifying system comprising an amplifier including means for introducing a phase shift of 180° additional to its overall phase shift and a feedback connection between the output and input circuits of said amplifier, said connection including a transmission line of length

$$l = \lambda \left(.5m - \frac{\phi}{360} \right)$$

where l =length in meters, λ =the amplifier's mid-band frequency, m is an odd integer, and ϕ is a phase shift in the amplifier due to the effect of electron transit time.

7. An amplifying system comprising an amplifier including means for introducing a phase shift of π radians additional to the normal phase shift between the input and output of said amplifier, and a feedback connection for said system including a transmission line of length $l = .5m\lambda$, where λ =the mid-band frequency of the signal to be amplified, m is an odd integer, and l is in meters.

8. A transmission system comprising a μ - or forwardly transmitting path and a β - or backwardly transmitting path, said μ -path having a phase shift therein due to the effect of electron transit time and said β -path containing means compensating for said phase shift, said means including an electron discharge device.

9. An amplifier having a μ - or forwardly transmitting path, and a β - or backwardly transmitting path, said μ -path comprising an electron discharge device, the phase shift between the input and output of said device including a phase shift because of the effect of electron transit time at the frequency being amplified, and means in the β -path to compensate for the transit time phase shift, said means comprising a series impedance and a shunt impedance, said shunt impedance comprising an electron discharge device having a cathode and an anode, and a choke coil connected between said cathode and anode.

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